Study on the Application of Temperature Difference in the Evaluation of Pipe Break Size in Recirculation Systems Based on Thermal-hydraulic Model Analysis

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ABSTRACT

This study investigates the temperature difference between recirculation loops following an instantaneous pipeline rupture. The analysis shows that the pipe rupture leads to the conversion of energy at an open system, resulting in the coolant escaping from the broken exhibiting a lower temperature compared to the intact loop. A theoretical model, based on energy balance principles, effectively explains these temperature differences. Validation through the Modular Accident Analysis Program (MAAP5) simulations and training simulator results confirms that both tools accurately predict temperature changes during station blackout and loss of coolant accident scenarios. This study examines the effects of coolant pipe ruptures on the recirculation system and compares the resulting trends with the simulator data. The model can serve as a foundation for future quantitative research, enabling a deeper understanding of the recirculation system during a break transient period. The use of computer simulation codes will ensure the main phenomena, improve accident management strategies and establish a basis for future quantitative analyses. And, the results of this study also indicate that the correlation between the temperature difference between pipelines and the break size of pipelines is more strongly assisted to the peak cladding temperature.

Keywords: temperature difference, break size, MAAP5, recirculation loop

INTRODUCTION

The loss of coolant accident (LOCA) in a nuclear reactor's recirculation system represents a significant threat to reactor safety and is a critical area of nuclear safety research [1]. A LOCA can have severe consequences, potentially leading to the overheating of the reactor core. In such an event, the loss of coolant may cause the fuel rods to fail, resulting in the release of radioactive materials into the containment structure. If the containment system is inadequate or fails, there is a risk of radioactive substances escaping into the environment, posing a serious threat to public health and safety. Additionally, a LOCA could initiate a cascade of failures in safety systems, complicating efforts to stabilize the reactor and manage the emergency, which may escalate the severity of the incident. While many studies focus on the most severe scenario, typically involving a ruptured recirculation pipe, the majority of discussions concentrate on analyzing peak cladding temperatures, fuel rod failure, and oxidation levels in relation to safety criteria. There is, however, less attention given to the symptoms that may indicate the origin of the cause of rupture itself.

Hou *et al*. conducted safety analyses on the CNP 600 reactor using the RELAP5 program, investigating the variations in key system parameters across different break sizes in the recirculation loops during a LOCA. Their study revealed a strong correlation between break size and coolant temperatures at the inlet and outlet of the recirculation loops [2]. Similar findings were also graphically represented in data from JAERI's ROSA-III simulations [3-5]. For LOCA calculations, the plant behavior and Peak Cladding Temperature (PCT) results predicted by the RELAP5 model were consistent with those reported by GEH [6].

Wang *et al*. simulated key severe accident phenomena such as core uncover, cladding oxidation, cladding failure, debris relocation to the lower plenum, and vessel head failure. Their findings indicated that the results from SR5, MAAP, and MELCOR were highly consistent in modeling critical phenomena during accidents, including steam generator dryout, core uncover, cladding oxidation, molten pool formation, debris relocation, and vessel head failure [7]. Additionally, Yasuharu *et al*. demonstrated that both MAAP and RELAP5 produced consistent results in formulating incident management strategies, even in the absence of specific mitigation measures [8].

At the 9th European MELCOR Users Conference held in Spain in 2017, Mascari *et al*. reported that the predictions of LOCA progression by ASTEC, MAAP, and MELCOR showed strong qualitative consistency, although some quantitative differences were

noted. For example, when analyzing the time sequences of related phenomena, the maximum percentage difference in selected key safety parameters, referred to as the “figure of merit," between ASTEC and MAAP/MELCOR was approximately 20% [9]. The “figure of merit,” also known as a characteristic value, is a performance metric used to evaluate the effectiveness of equipment, systems, or methodologies. The consistent predictions of transient phenomena by all three codes validate their reliability in modeling the progression of reactor accidents [10]. Furthermore, a 2013 technical report on the application of the MAAP code to post-Fukushima accident analysis demonstrated that MAAP performed exceptionally well, with results closely aligned with those of the reference plant [11]. This highlights that the accident analysis software commonly used in the industry can provide consistent trends for the accidents being analyzed.

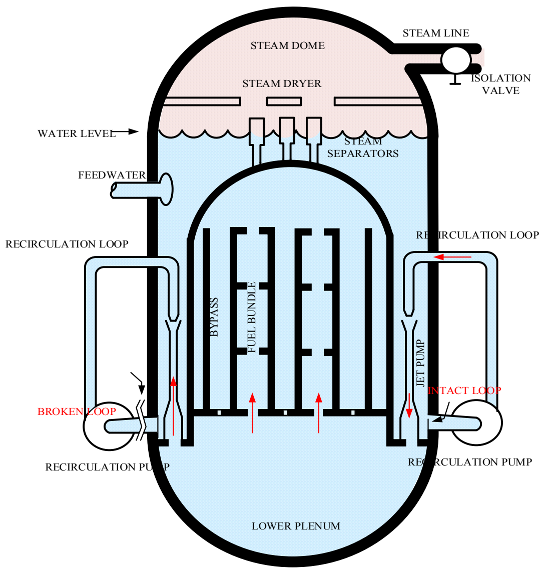
Hwang’s research further validated the accuracy of the MAAP5 program in simulating the relationship between LOCA break sizes and temperature differences [12]. The study found that different break sizes significantly affected the temperature differences between the inlet and outlet of recirculation pipelines and established a corresponding relationship between these temperature differences and the size of the pipeline break. This discovery has promising practical applications, as operators can estimate the break size by monitoring temperature differences between pipelines without relying on additional external instruments. This not only improves the efficiency of accident assessment but also provides crucial information for ensuring reactor safety during the critical seconds immediately following an accident. This discovery holds significant practical value. In the event of a LOCA, operators can quickly assess the rupture size by monitoring the temperature differences between the recirculation loops, enabling faster decision-making and enhancing reactor safety during the critical moments following an accident. However, the study also indicated that temperature difference fluctuations are influenced by the system recovery strategy implemented after the rupture. Consequently, further research is necessary to comprehensively understand the behavior of temperature differences caused by pipeline ruptures, laying the groundwork for optimizing diagnostic tools and recovery strategies.

The objective of this study is to develop a model that qualitatively describes the characteristics of the temperature variation phenomenon when pipe ruptures occur. The model bases on the principles of heat transfer, fluid dynamics and energy balance, and hopes to establish a qualitative model to further clarify this phenomenon and lay the foundation for future in-depth research. By employing computer simulation

programs, this study analyzes the effects of coolant pipe ruptures on the recirculation cooling system and compares the resulting trends with data from operator simulators. To further understand why the intact loop exhibits a higher temperature than the broken loop.

METHOD

During a LOCA in a nuclear power plant, temperature differences appear between the intact and broken sections of the recirculation loop. This study examines how pipe ruptures lead to these differences by analyzing trends, comparing results with BWR6/MARK-III simulator data, and conducting further MAAP5



simulations.

Figure 1 Steam and recirculation water flow paths in a BWR, and the relevant location of the experiment [12].

Figure 1 illustrates the locations and coolant flow direction during the LOCA experiment. Before any rupture, both recirculation loops are identical in temperature and pressure. When rupture occurs in loop A, its state diverges from the intact loop B. Figure 2 separates the ruptured pipe A and intact pipe B, highlighting their distinct states. Where the red line depicts the flow direction of the recirculation cooling water following the LOCA accident.

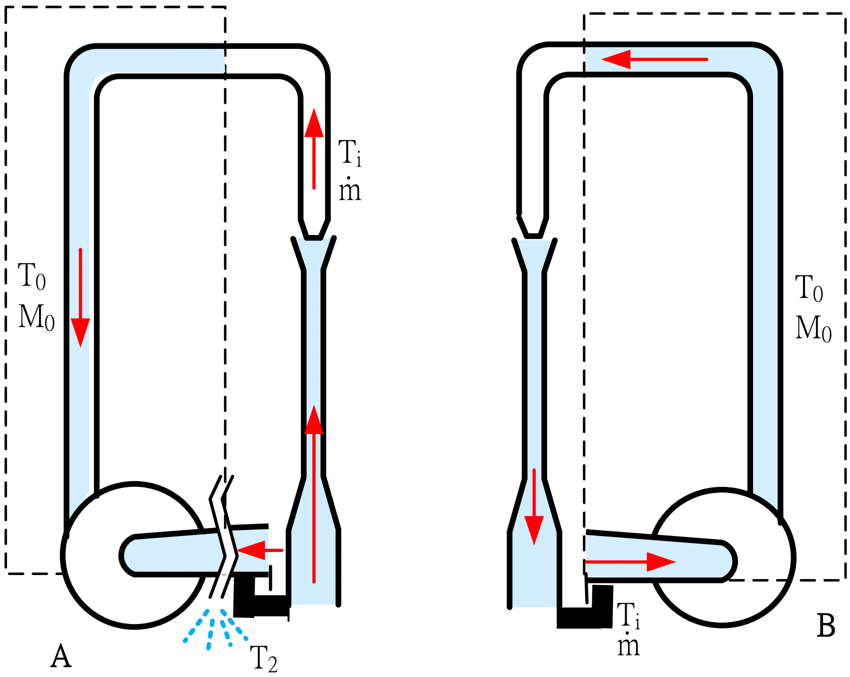


Figure 2: Schematic diagram of the volume region between temperature and pressure at the broken pipe A and the intact pipe B [13].

And:

T_i is the temperature of the countercurrent flow from the lower plenum into the broken recirculation loop, which is related to the decay heat time.

T_0 is the original temperature at the recirculation loop, which is influenced by the injected coolant T_i.

T_2 is the bulk temperature after the break, which decreases over time.

M_0 represents the coolant mass at the control volume.

$\dot{m}$ is the coolant mass flow rate of the countercurrent flow from the lower plenum into the broken recirculation loop.

The dash line indicates the control volume.

The rate of change of energy within the control volume equals the net rate of energy transfer into and out of the control volume, as the related formula derivation Equation (1).

$$\frac{dU_{acc}}{dt} + \Delta\left(\widehat{H} + \widehat{K} + \widehat{P}\right)\dot{m} = \dot{Q} + \dot{W} \quad (1)$$

When the control volume has only one entrance and one exit, and under the assumption of no heat source and no work (i.e., $\dot{Q} = 0$, $\dot{W} = 0$), and

neglecting variations in $\Delta \widehat{K}$ and $\Delta \widehat{P}$, we obtain the following equation:

$$M_0 \widehat{C_v}\, dT + \dot{m}\, \widehat{C_p}\, (T - T_i) = 0 \qquad (2)$$

Where:

- U_{acc} is the internal energy accumulated in the control volume
- $\dot{m}$ is the mass flow rate into the control volume.
- M_0 is the constant mass in the control volume.
- $\widehat{C_v} = \widehat{C_p}$ represent specific (or per unit mass) heat capacities.
- $\widehat{H}$ is the enthalpy per unit mass.
- $\widehat{K}$ is the kinetic energy per unit mass.
- $\widehat{P}$ is the potential energy per unit mass.

Based on Ferng's[14] and MAAP's report[15], the mass flow rate $\dot{m}$ can be expressed as:

$$\dot{m} = C_d \bullet A \bullet \left[\frac{2P(1-\eta)}{v_l}\right]^{\frac{1}{2}} \qquad (3)$$

where:

- $\dot{m}$ = Flow rate through the break
- A = Break area
- C_d = Discharge coefficient
- P = Upstream pressure at the break
- V_l = Specific volume of the fluid
- $\eta = Max\ (P_{rec}/P, \eta_{crit})$
- P_{rec} = Downstream pressure at the break
- $\eta_{crit} = Min\ (\eta_{crit}*, P_{sat}/P)$
- $\eta_{crit}* = 0.83 - (0.15/0.22)x$ for $x \leq 0.2$

Solving for temperature variation using the separation of variables method: with the initial temperature at the control volume T_0；Δt is time from scram t_s to t

$$\frac{dT}{T-T_i}=-\frac{C_d \cdot A \cdot \left[\frac{2P(1-\eta)}{v_l}\right]^{1/2}}{M_0}dt \tag{4}$$

After integration: and take the initial condition to Equation (4), When $t=t_s$, $T_2=T_0$, then $\Delta t=t-t_s$

$$ln\frac{T_2-T_i}{T_0-T_i}=-\frac{C_d \cdot A \cdot \left[\frac{2P(1-\eta)}{v_l}\right]^{\frac{1}{2}}}{M_0}(t-t_s)+C \tag{5}$$

$$T_2-T_i=k(T_0-T_i)^{-\frac{C_d \cdot A \cdot \left[\frac{2P(1-\eta)}{v_l}\right]^{1/2}}{M_0}\Delta t} \tag{6}$$

And $C=0$

Applying a Taylor series expansion for the exponential function:

$$e^x \simeq 1+\frac{x}{1!}+\frac{x^2}{2!}+..+\frac{x^n}{n!}+\mathrm{R}_n$$

$$R_n=\frac{f^{n+1}(\varepsilon)}{(n+1)!}(x-\xi)^{(n+1)}$$

And obtain:

$$T_2 - T_i = (T_0 - T_i)\cdot\left(1 - \frac{C_d \bullet A \bullet \left[\frac{2P(1-\eta)}{v_l}\right]^{\frac{1}{2}}}{M_0} t + \frac{1}{2!}\left(-\frac{C_d \bullet A \bullet \left[\frac{2P(1-\eta)}{v_l}\right]^{\frac{1}{2}}}{M_0}\right)^2 t^2 + \dots + \frac{1}{n!}\left(-\frac{C_d \bullet A \bullet \left[\frac{2P(1-\eta)}{v_l}\right]^{\frac{1}{2}}}{M_0}\right)^n t^n + \dots\right) \quad (7)$$

Further simplification yields:

$$T_2 - T_0 = (T_0 - T_i)\left(-\frac{C_d \bullet A \bullet \left[\frac{2P(1-\eta)}{v_l}\right]^{\frac{1}{2}}}{M_0}\right)t + (T_0 - T_i)\frac{1}{2!}\left(-\frac{C_d \bullet A \bullet \left[\frac{2P(1-\eta)}{v_l}\right]^{\frac{1}{2}}}{M_0}\right)^2 t^2 + \dots + \frac{1}{n!}(T_0 - T_i)\left(-\frac{C_d \bullet A \bullet \left[\frac{2P(1-\eta)}{v_l}\right]^{\frac{1}{2}}}{M_0}\right)^n t^n + \dots \quad (8)$$

The temperature difference $T_2 - T_0$ represents the coolant temperature change in the recirculation loop, which depends on the break area A and the pressure difference between the upstream and downstream of the break. Assuming constant pressure difference, $T_2 - T_0$ is directly related to the break area A. T_0 is the coolant bulk temperature in the pipeline, and T_2 is the coolant temperature after the break. According to Equation (7), the break cross-sectional area A is linked to the temperature difference $T_2 - T_0$. Before the break, the coolant temperature is T_0, and after the break, it changes to T_2, transferring internal energy via enthalpy.

And, if there is no rupture, there is no temperature difference within the considered volume in Figure 2, leading to $(T_0 - T_i)=0$ in Equation (7). Consequently, Equation (8) gives $T_2 = T_0$, indicating no temperature difference between the corresponding pipes in

the two loops when no rupture occurs.
When considering the decay heat Q after a scram, and with the ECCS safety injection, counter-current coolant flow occurs through the lower plenum to the break location, leading to $T_i < T_0$. In the absence of safety injection water, the coolant from the lower plenum is hotter than T_0, meaning that $(T_0 - T_i)$ can be either negative or positive.

Table 1 indicates that the signs (positive/negative) of each term in Equation (8)

$P(1-\eta)$	+	Pressure difference at the upstream/downstream of broken pipe
A	+	The cross section of the broken area
$(T_0 - T_i)$	+/−	The temperature difference between the pipe entrance and bulk depends on the decay heat transferred from the lower plenum.
M_0	+	The coolant mass at the recirculation loop of the control volume
C_d	+	The Discharge coefficient

Table 1 provides a detailed relationship or assignment of positive and negative signs to the various terms in the Equation (8).

Due to the fact that the decay heat Q will continue to decrease with increasing shutdown time, T_i will exhibit a decreasing trend, and the overall coolant temperature T_0 inside the tube will also drop. Consequently, the temperature difference between T_i and T_0 in Equation (8) will show both positive and negative variations over time.
When $T_i > T_0$, it indicates that the temperature in the break loop is higher than that in the intact loop; conversely, when $T_i < T_0$, the coolant temperature in the intact loop will be higher than that in the break loop. Therefore, the presence or absence of water injection will be the key factor affecting the temperature difference, this will be discussed later.
In Equation (6), R_n represents the n-th order error of f(x). Its value decreases as x gets closer to the center point ξ and as the order n increases, making the approximation of f(x) more accurate.
MAAP5 simulates accident progression and impact analysis by considering factors such as pressure, fluid properties, and break geometry. The mass flow rate in the broken pipe is directly proportional to the pressure difference between the upstream and downstream, as shown in Equation (8). As the break size increases, the mass flow

rate also increases, even if the pressure difference remains constant, until it reaches a critical flow state. At this point, the outflow rate no longer increases, and the mass flow rate reaches its critical value [14].

Equation (8) also shows that the temperature difference across the broken loop is directly proportional to the pressure difference at the break. As the break size increases, the temperature difference between the loops increases. Once the mass flow rate reaches its critical value, the temperature difference no longer increases and instead reaches a maximum across different break sizes. Based on this, the maximum temperature difference between the two loops can be determined.

VALIDATION AND EVALUATION

The scenario is designed to simulate a recirculation loop suction-side LOCA event occurring during normal operation. The break leads to a rapid pressure drop, triggering a reactor scram. It is assumed that the ECCS can successfully activate to makeup the coolant. The temperature variations between the broken loop and the intact loop are observed under this condition.

For this study, SBO [16] and LOCA scenarios [17] were selected as key indicators for simulation and qualitative assessment. To ensure the accuracy, reliability, and validity of the research conclusions, this study uses data from a simulator designed specifically for the reactor system.

SBO is a severe accident scenario, however, the coolant loops remain intact. Comparing LOCA and SBO events, a standalone SBO event causes a reactor scram while keeping the piping intact. In contrast, a LOCA event not only triggers a reactor scram but also involves a break in the loop, leading to coolant loss. Through the SBO and LOCA experiments, we can confirm that the temperature difference is caused by a rupture in the corresponding loop.

SIMULATOR RESULTS

Figure 3 illustrates the temperature data during an SBO accident as simulated by the simulator, and the temperatures are always at 277℃ to both loop A and loop B, are consistence to the FSAR. The yellow line indicates the temperature difference between the two recirculation loops. The horizontal trend of the line shows no significant temperature difference, as there is no break in the loops. The green and blue lines represent the temperatures of the intact and broken loops, respectively, which nearly overlap due to the absence of a rupture. The yellow line indicates the temperature difference between the two loops, which remains near zero. According to Equation (8), since both Loop A and Loop B at the SBO scenario are intact and undamaged, then we have $T_i=T_0$ and $T_2=T_i=T_0$ in both loops A and B. This result is consistence to the prediction of Equation (8), no break no temperature difference.
To compare with the SBO scenario, an experiment involving a LOCA was conducted, focusing on a rupture in recirculation loop A.

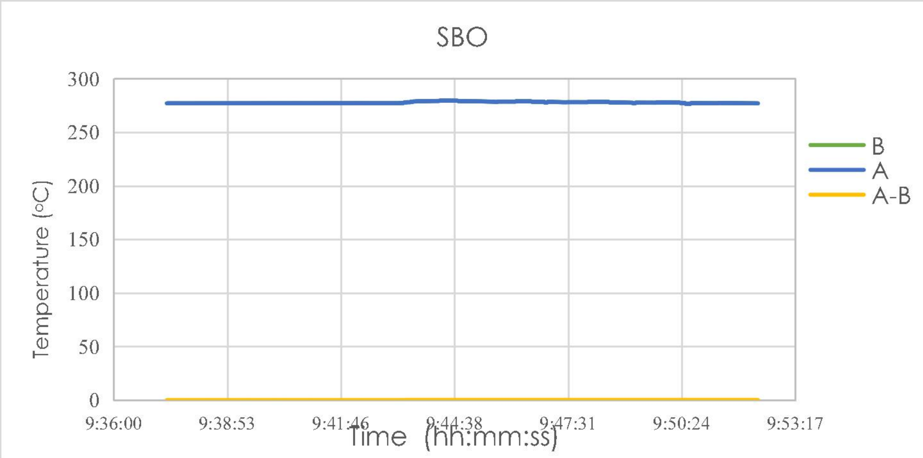


Figure 3 shows the results from a training simulator depicting the temperatures of the two loops and the temperature difference between them during an SBO accident, with no breaks present in either loop.

Figure 4 shows the simulator data for the LOCA event. The rupture caused a significant temperature difference between the two loops loop A and loop B. Before the break occurred at 14:36:14, the reactor was in normal operating conditions. After the LOCA, the temperature difference between the loops increased, exceeding 40°C, and lasted for 150 seconds. While the exact break size cannot be determined due to the simulator's limitations designed for training rather than experimental precision, the data clearly indicate that a pipe rupture leads to a significant temperature difference between the intact and broken loops.

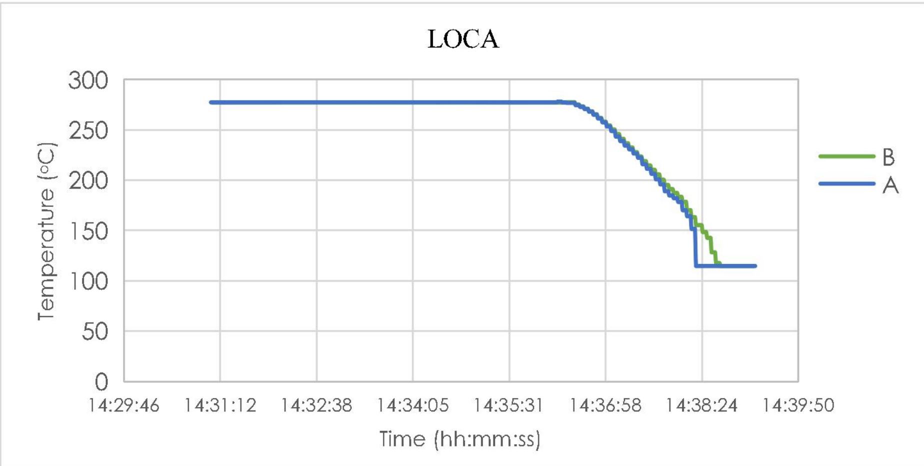


Figure 4 shows the simulated temperatures at the inlets of loops A and B during an LOCA, as generated by the training simulator.

In Figure 4, the reactor scrammed at 14:36:21, and the temperature difference between the inlet recirculation loops began to increase until 14:38:24, lasting

approximately 150 seconds. Comparison of Figures 3 and 4 confirms that the temperature difference observed was due to a pipe break rather than a SBO. The temperature difference became apparent after the reactor scram, as shown in the simulator results depicted in Figure 4. The temperature difference that observed is a temporary condition. The temperature difference phenomenon shown in Figure 4 appears from 14:36:21 to 14:38:24, the duration last about 2 minutes, after which it remains constant without temperature difference. Temperature difference observed is a temporary condition that occurs during the LOCA event rather than the SBO event.

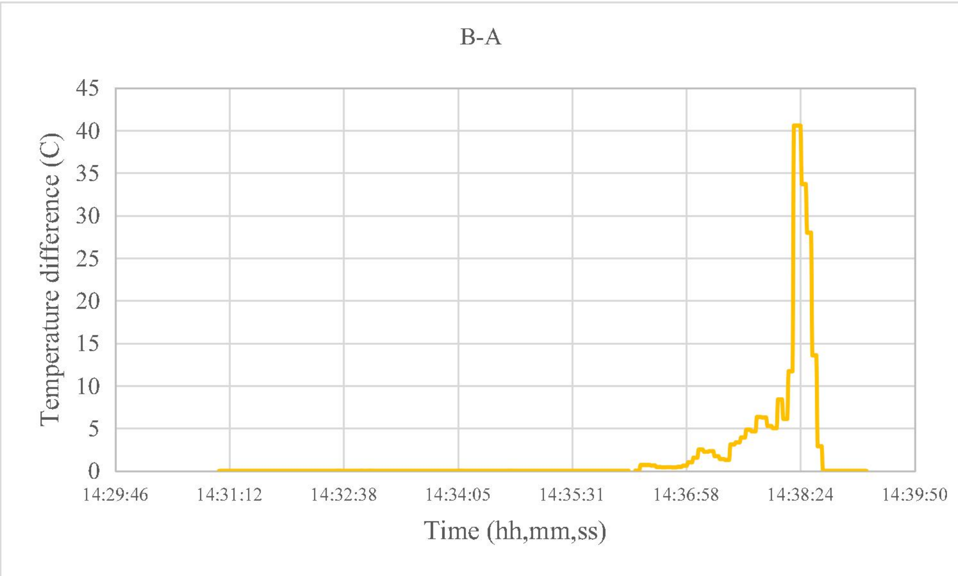


Figure 5 shows the simulated temperatures difference between the inlets of loop A and loop B during LOCA, which was generated by the training simulator.

Figures 3 to 5 illustrate the outcomes of the simulation conducted by the BWR6/MARK-Ⅲ simulator. Although the simulator is a valuable tool to observe the sequence of changes in the reactor following parameter difference, it is primarily designed for the education and training of reactor operators rather than for case studies; even the break sizes can be adjusted, but cannot know the real break size.

MAAP5 RESULT

This section applied the MAAP5 program to simulate the SBO and LOCA experiments above and compare the results with those obtained by the derived formula Equation (8). According to the FSAR [18], the design pressure is 7.172×10^6 pa (1040 psi). The pressure simulated by the MAAP5 program is 7.189×10^6 pa (1042 psi), while the simulator shows 7.215×10^6 pa (1045.7 psi). The temperature at the recirculation loops is 551 K, and according to the FSAR, it is 549 K when simulated by MAAP5 and 550 K by the simulator. This indicates that the

simulation errors for both temperatures and pressures in MAAP5 and simulator; compared to the FSAR the errors are less than 0.3%.

Table 2 the temperature and the pressure noticed in FSAR, simulator, and MAAP5

	FSAR	Simulator	MAAP5
Temperature (K)	551	550	549
Pressure (pa)	7.172×10^6	7.215×10^6	7.189×10^6

Figures 6 and 7 demonstrate that the MAAP5 simulations of SBO and LOCA scenarios align with the trends observed in the training simulator. According to Equation (8), the temperature in the intact loop is higher than that in the broken loop, or conversely the temperature in the broken loop is lower than in the intact loop. Since coolant flow through the rupture reaches a critical value at a certain pressure, the temperature difference is expected to have a maximum for a specific break size, as the former description.

Thus, in the MAAP5 simulation results, the maximum temperature difference was identified for each break size, validating the consistency between the MAAP5 program and the training simulator for both SBO and LOCA conditions.

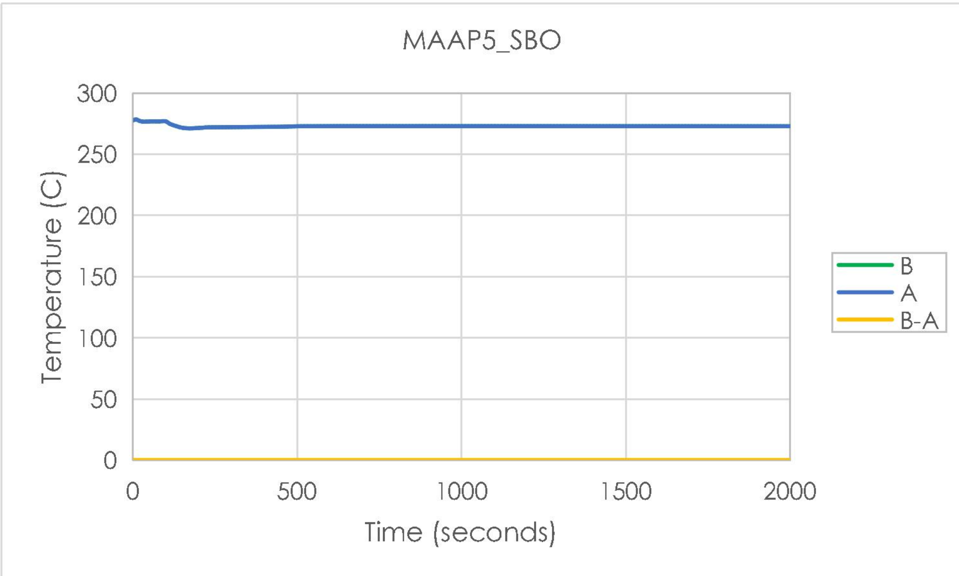


Figure 6 demonstrated the MAAP5 to simulate the SBO in a BWR6/MARK-Ⅲ

Figure 7 presents the LOCA results obtained from simulations using the MAAP5 program, which are consistent with the trends shown in Figure 4 from the training simulator. Since the simulator is based on data retrieved from resistance temperature detectors (RTD) from the power plant, and considering that each sensor has its

detected limits, therefore all data below 0.4°C are considered as noise in the simulation, as it falls within the detection limit of the RTD[19].

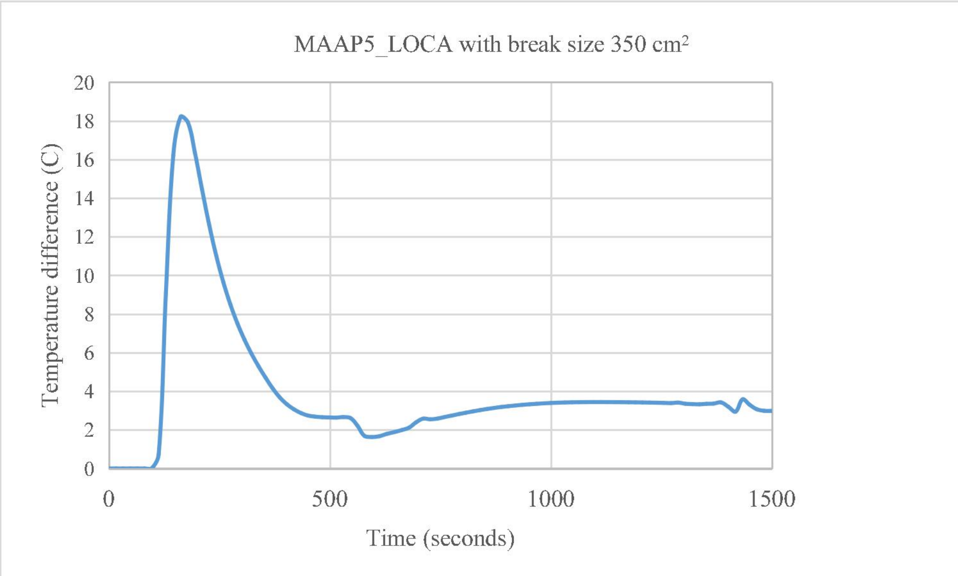


Figure 7 demonstrated the MAAP5 to simulate the LOCA in a BWR6/MARK-Ⅲ

Figure 7 presents the LOCA simulation results from MAAP5 program, which align with the LOCA trends observed in Figure 4 from the training simulator. After the reactor scrammed due to a break in the recirculation loop, caused coolant loss, a temperature difference is evident between the intact and broken loops. This LOCA phenomenon is clearly shown by both the MAAP5 simulations and the training simulator in Figures 5 and Figure 7 displaying a same trend. The consistency between the MAAP5 simulations and the training simulator validates the reactor characteristics observed in both tools. According to EPRI, 2013, the MAAP formula for BWR reactors in LOCA accident transients from 7 min. to 40 hrs has good consistency with the response of various reference power plants [11]. And Ferng demonstrated that the MAAP program's RCS model primarily simulates the thermal-hydraulic response, thermodynamic properties of the cooling water, and the transient rate of change in system parameters in his research report [14].

The results demonstrate that both the simulator and the MAAP5 produced consistent response patterns. It has been confirmed through the SBO and LOCA experiments that the temperature difference is caused by a rupture in the corresponding loop.

DISCUSSION

Previous cross-validation between the SBO and LOCA simulators and MAAP5 has shown that the break is the primary factor responsible for the temperature difference. This section compares these results with those from a simplified model, and our analysis confirms the relationship between the rupture mechanism and the temperature difference.

Following an instantaneous pipeline rupture, the system remains initially unchanged, while the temperature difference between loops gradually increases. During a LOCA, the recirculation pump stops, causing reverse flow in the broken loop, while the intact loop continues briefly due to coolant inertia. Backflow through the jet pump may mix with hotter core coolant ($T_i > T_0$) or ECCS coolant ($T_i < T_0$). The reverse flow carries hot coolant from the core through the lower plenum and jet pump, exiting via the break, influencing the overall temperature difference. Equation (8) shows this difference depends on break size and follows an exponential or first-order polynomial function, requiring experimental validation.

CASE 1. $T_i > T_0$

This scenario occurs after a reactor LOCA scram, where all emergency cooling systems remain inactive, leaving only the decay heat from the core fuel to heat the gradually decreasing reactor water, as Figure 8 demonstrated.

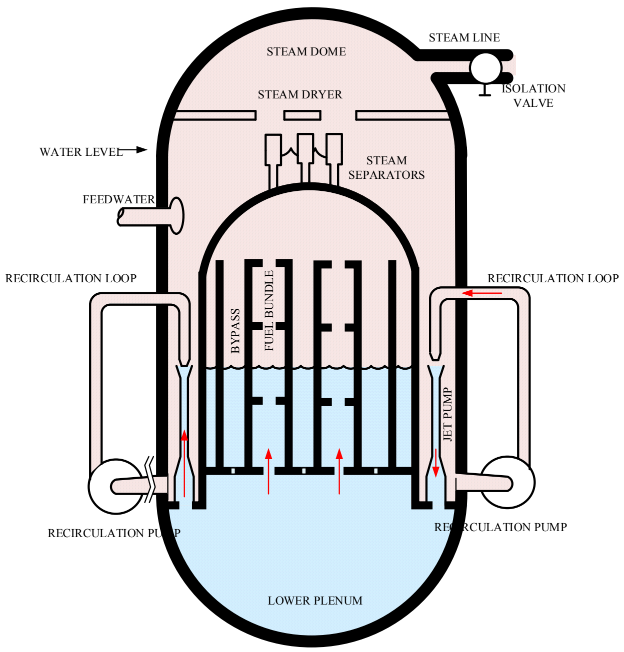


Figure 8. a consequence of LOCA without any safety injection water

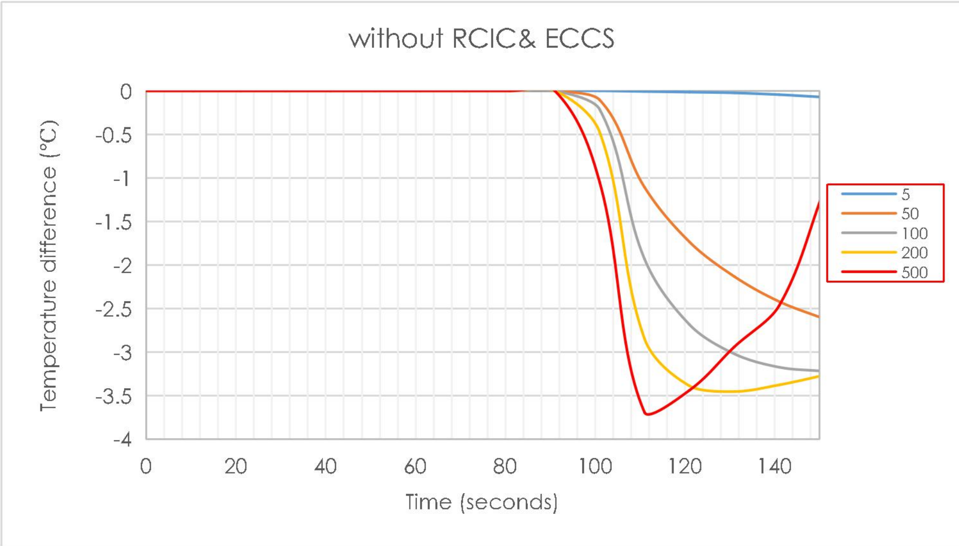


Figure 9.without the rescued coolant to save the core after the reactor scram

The reverse flow directs the hotter coolant from the reactor core through the lower plenum and jet pump, exiting through the break. Figure 9 clearly shows that when the reactor undergoes a scram due to a LOCA caused by breakages of different sizes, and no emergency injection is provided, the condition $T_i > T_0$ occurs. According to the prediction of Equation (8), the temperature of the broken-loop should be higher than that of the intact loop as $T_i > T_2 > T_0$. The results predicted by this model are consistent with those simulated by MAAP5.

CASE 2. $T_i < T_0$

Due to the reactor's scram caused by a rupture in the recirculation loop, the high core pressure forces a large amount of coolant to be discharged in reverse from the break. At this time, all designed water injection systems will activate according to their intended functions. The injection water is sourced from facilities such as the condensate storage tank (CST) or the suppression pool, with its temperature typically set at 60°C far lower than the reactor's normal operating temperature of 277 °C. Therefore, as long as any one injection system operates normally, the condition $T_i < T_0$ is maintained. According to the relationship of heat transfer that $T_i < T_2 < T_0$.

This analysis reveals that the counter current flow temperature in the broken recirculation loop affects its internal water temperature, leading to a temperature difference between the loops.

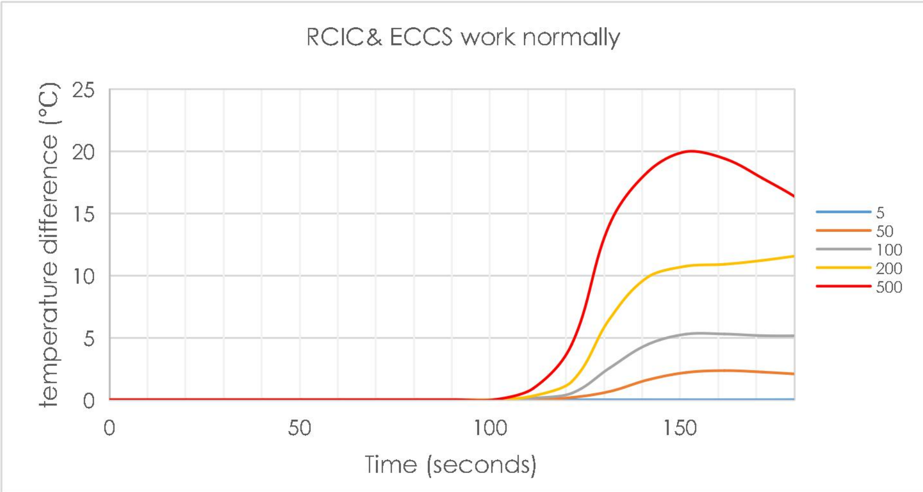


Figure 10. After the LOCA-induced scram, all safety injection systems function as originally designed.

The previous study confirmed that the temperature of the counter-current flow coolant causes different temperature difference patterns at the break. Furthermore, based on Equation (8), the temperature difference is related to the break area, as shown in Figures 9 and 10, and can be expressed in the form of Equation (9).

$$(T_2 - T_0) \propto (-A\ [\frac{P}{V}\frac{(1-\eta)}{l}]). \quad (9)$$

Herein, the assumption of a constant pressure difference may not be entirely accurate. However, in according to the definition of breaks, which are categorized into large, medium, and small breaks. Typically, a break area equivalent to 10% of the main coolant pipe's cross-sectional area serves as the threshold between large and medium breaks, while 2% of the pipe's cross-sectional area serves as the boundary between medium and small breaks [20]. Therefore, for a 20-inch pipe, a break size of 300 cm^2 falls into the large break category. In Figure 10, the curves in different colors represent the pressure of breaks to various sizes, ranging from 6 cm^2 to 600 cm^2, when the data were collected. When the pipe line is broken, and the pipe internal pressure drops from 7.189×10^6 pa (1042 psi) to 6.576×10^6 pa (957 psi), a reduction of 8.3% to a 300 cm^2 break. The impact of the pressure drop caused by the break on the system is less than 10% within 300 seconds. If the break is even smaller, the pressure difference decreases further, with a change of only about 5%. Therefore, the relationship $(T_2 - T_i)$ in Equation (9) can be approximated as proportional to the break size within a certain range. And, the pressure drop in the reactor cooling system after the break occurs is a function of time, as shown in Figure 11.

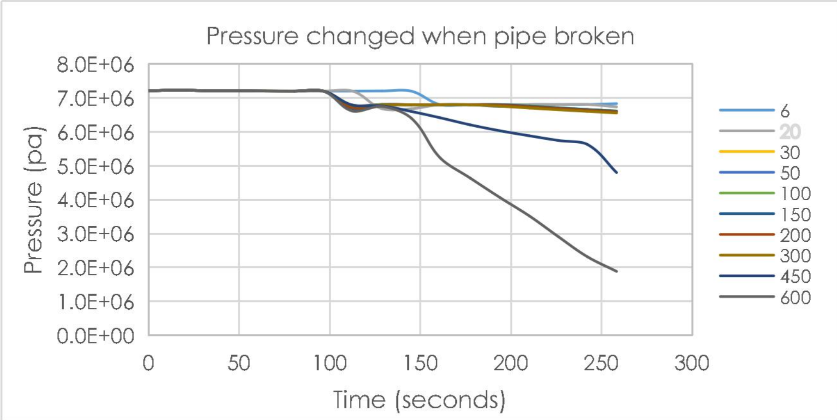


Figure 11 shows the pressure curves in different colors representing breaks of various sizes, ranging from 6 cm² to 600 cm².

For each different break size, there should be a corresponding maximum break flow rate and maximum pressure drop. Ferng's report also shows that the mass flow rate of the break is proportional to the pressure difference between the upstream and downstream. When the pressure difference between the upstream and downstream reaches a certain level, the break flow rate will reach a certain value and will no longer continue to increase. Therefore, as the break size increases, the mass flow rate also increases, even if the pressure difference remains constant, eventually reaching a critical flow state. Thus, a maximum temperature difference corresponding to different break sizes. In the absence of water injection, the reactor core will be exposed within a few minutes to several tens of minutes, depending on the break size.
The simplified model derived in Equation (8) can reasonably predict the relationship between the break and the temperature difference, applying to both water injection and non-water injection scenarios. Additionally, it can quickly assess the break within a short period, as demonstrated by the following Figure12 and Figure 13.

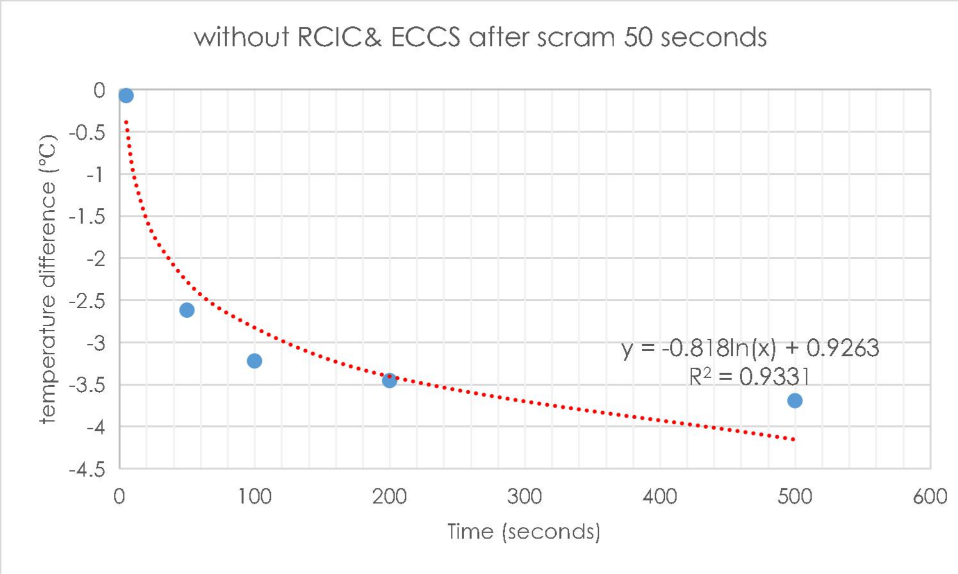


Figure 12 the break size spectrum at 50 seconds after the reactor scram

Figure 12 showed a result that the primary observed phenomenon is that the temperature in the intact loop is higher than in the broken loop. The figure shows that without the RCIC and ECCS systems for backup, the coolant temperature in the broken loop is higher than in the intact loop. This is primarily due to the high-temperature water from the reactor core flowing through the lower plenum and then through recirculation loop to the break location.
No RCIR and ECCS is only in extremely rare cases where water injection is entirely unavailable or during the transient moment of the break might the broken loop's temperature exceed that of the intact loop. In Equation (8) $T_i>T_2>T_0$, both the left-hand side and the right-hand side are positive, indicating that the temperature in the broken loop is higher than in the intact loop. Basically, the probability of this situation occurring is very low.

Under normal operating conditions, a break triggers an emergency reactor shutdown, followed by sequential RCIC and ECCS water injection. In Figure 13 shows the temperature deviation between the broken loop and intact loop. In Equation (8) $T_i<T_2<T_0$, here both the left-hand side and the right-hand side are negative, indicating that the temperature in the intact loop is higher than in the broken loop. Normally, as long as the reactor's backup cooling system operates properly, it can effectively cool the reactor core.

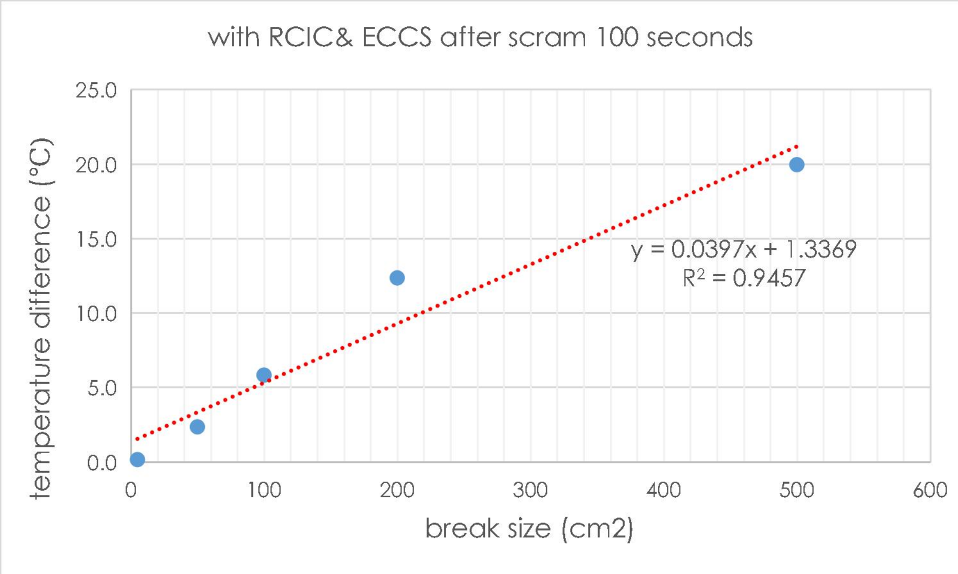


Figure 13 the break size spectrum at 100 seconds after the reactor scram

In Excel, the R^2 value of a linear trend line is a statistical measure used to evaluate how well the fitted model matches the actual data. Therefore, the R^2 values of the fitting function are also posted in Figures 12 to 13.

The data and functions of the fitted curves in Figures 12 and 13 show a correlation of over 90%, indicating that shortly after a reactor scram, Equation (8) still aligns with the characteristics of this open system.

R^2 range: from 0 to 1.R^2=1 indicates a perfect fit: all data points fall exactly on the trends line, meaning the model explains all of the data variation. R^2=0 indicates no fit: the trend line does not explain any of the data variation. In Figures 11 through Figure 12, the trend lines and its R^2 values corresponding to the sampling times are clearly indicated, showing that as the sampling time increases, the R^2 value of the trend lines decreases.

In Figures 12 and 13. The distribution of these blue dotted points is approximately fitted by the red dashed line, with the corresponding temperature differences also included. The results show that the MAAP5 simulation aligns with the constructed model, Equation (8), indicating that when the safety injection system is activated, the intact loop temperature is higher than the broken loop temperature. This provides a theoretical foundation for further research and application.

The temperature difference of the broken pipe does exhibit a linear relationship with the break size, as calculated by the fitting equation posted in the figures, according to Figure12 linear fitting curve of the MAAP5 data, which is ~95% consistent with the properties of a straight line with zero intercept. According to EPRI, 2013, the MAAP

formula for BWR reactors in LOCA accident transients from 7 min. to 40 hrs has good consistency with the response of various reference power plants [10].

This verifies the rationality of the relevant assumptions and provides an important basis for understanding the thermal response characteristics of the system. However, the temperature difference of the broken loop in Equation (8) and the broken flow rate in Equation (3) show that the smaller the downstream pressure, the greater the broken flow rate, that is, the larger the break is; the above Equations (3) and (8), both expressions show that they are related to the fracture break size and pressure difference.

CONCLUSION

This study uses the MAAP5 program to analyze variations temperature and pressure differences in reactor cooling system, in a BWR6/MARK-Ⅲ nuclear power plant during LOCA and SBO events, and their effects.

(1) This study confirms that the temperature difference in the recirculation loop is caused by emergency injection water flowing in counter current flow through the break. And, given the presence of a critical flow rate at the break, selecting the maximum temperature difference within the sampling period is a reasonable approach in this study.

(2) Under normal operating conditions, a break leads to a reactor scram, followed by sequential ECCS water injection. This results in the primary observation that the intact loop maintains a higher temperature than the broken loop, thus the observer always obtains a higher temperature in intact loop. However, in rare cases where water injection fails or during the initial transient phase, the broken loop may temporarily exhibit a higher temperature.

(3) The MAAP5 simulation results align with the predictions of Equation (8) and numerical simulations, confirming that the temperature difference between loops is influenced by break size.

(4) Furthermore, based on simple estimation, the magnitude of the temperature difference can indeed be linked to the size of the break.

It should be noted that this analysis uses the BWR6/MARK-III as an example, but the findings are not limited to this model. MAAP5 simulation data aligns with these findings, confirming the robustness of the model and suggesting further applications for system response analysis and simulation tool development. Future work can further explore the relationship between break size and temperature difference to enhance the safety and reliability of reactor operations. And, for further calibration of the MAAP5 program with the real reactor parameters to enhance its accuracy in modeling pipeline rupture scenarios.

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